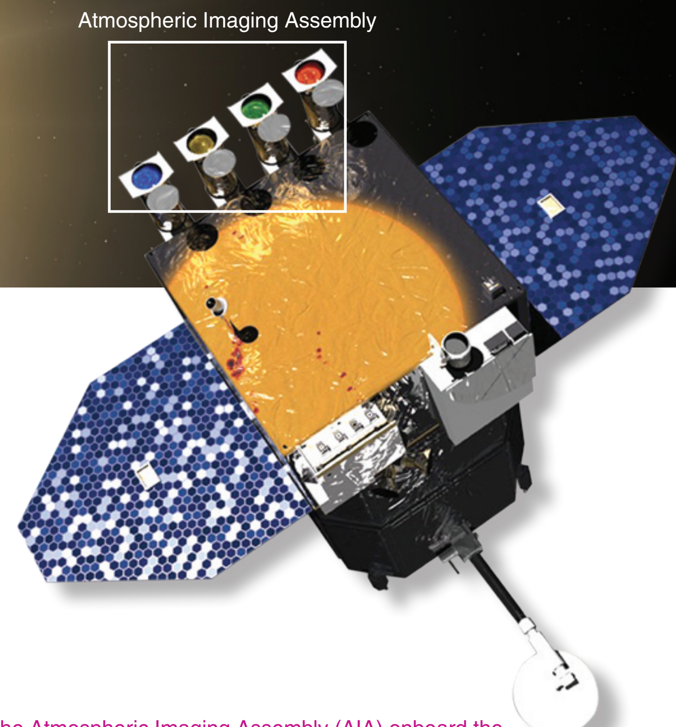
The Sun in All Its Splendor



The Atmospheric Imaging Assembly (AIA) onboard the Solar Dynamics Observatory (SDO) is a suite of four telescopes that image seven wavelengths of extreme ultraviolet light emitted from the Sun. (Courtesy of the National Aeronautics and Space Administration [NASA].)

THE Sun is the lifeblood of our planet. It provides the light, heat, and energy to Earth that is essential for perpetuating the existence of all living things. But as important as this star is, relatively little is known about its physical processes and often-volatile behavior. On February 11, 2010, the National Aeronautics and Space Administration sent the Solar Dynamics Observatory (SDO) into orbit to capture the highest temporal and spatial resolution, full-disk images of the Sun ever acquired. By studying the solar corona in more detail, researchers expect to learn more about the Sun's magnetic field, enabling them to better understand solar events that can adversely affect satellite communications, power grids, and many other aspects of life on Earth.

Onboard SDO is the Atmospheric Imaging Assembly (AIA), a suite of four telescopes that contain highly reflective multilayer mirrors codeveloped at Livermore. These sophisticated optics consist of two materials layered in a repeating sequence on top of a mirror substrate and allow AIA to image the Sun at seven wavelengths of extreme ultraviolet (EUV) light. Each EUV wavelength corresponds to an emission line of ionized solar materials (iron or helium) at different temperatures. AIA images all seven EUV wavelengths (and three additional ultraviolet and visible wavelengths) every 10 seconds to create "snapshots" of distinct features within the Sun's atmosphere at a resolution 10 times greater than that produced on a high-definition television. The AIA project at Livermore was funded by the Smithsonian Astrophysical Observatory, and the AIA principal investigating institution is Lockheed Martin Solar and Astrophysics Laboratory in Palo Alto, California.

Deposition of multilayer thin films was first attempted in the 1940s, but the technology of the time and the choice of materials were inadequate to create layers that would maintain stable interfaces when stacked one on top of the other. Three decades later, the first viable multilayer coatings were developed. Soon after, Livermore researchers became leaders in advancing multilayer thin-film coatings for a variety of physics applications and for EUV lithography, a technology that uses reflective multilayer mirrors for manufacturing improved computer chips. (See *S&TR*, October 2003, pp. 8–9.) Says Livermore physicist Regina Soufli, who led the Laboratory's SDO optic development team, "The improved multilayer mirror technologies created during our pursuit of EUV lithography made the SDO optics possible."

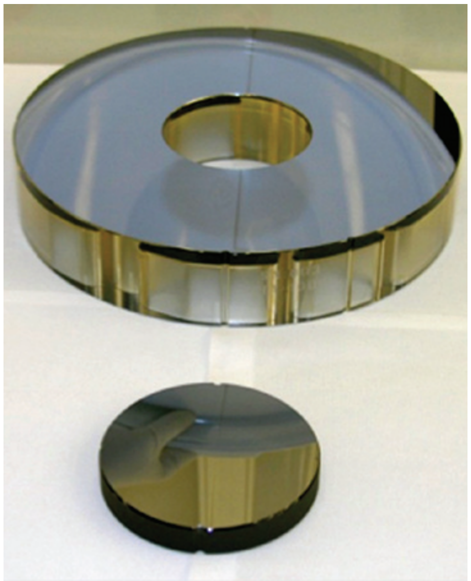
A Material Worth "Bragging" About

EUV wavelengths range between 50 and 5 nanometers, which coincide with the characteristic absorption wavelengths of inner-shell electrons in the atoms that compose matter. As a result, EUV light directed onto a standard mirror or lens at normal incidence is absorbed rather than reflected, making it undetectable. For this reason, EUV light is also absorbed by Earth's atmosphere, which is why telescopes must travel to space to study the light emitted from the Sun.

Multilayer mirrors achieve high reflective performance by acting as synthetic Bragg crystals. This effect is created by layers of materials deposited in a periodic stack. Through constructive interference of the reflected electric fields across the layers, these structures can efficiently reflect radiation at specific wavelengths according to Bragg's law, a formula that relates the reflected wavelength to the angle of the incident light and the periodic thickness of the individual layers. "For example," says Soufli, "we used a structure made from 50 molybdenum–silicon bilayers, each a few nanometers thick, to achieve optimum optical contrast and thus the highest reflectivity for EUV light at normal incidence."

Silicon and molybdenum are one of the few material combinations that can produce the right contrast for the solar wavelengths of interest on SDO. This material pair also has a history of stability, durability, and reliability in EUV-related applications, which made it an obvious choice for four of the SDO EUV wavelengths. Collaborators from Reflective X-Ray Optics, LLC, in New York City, used other material combinations as well, such as molybdenum–yttrium and silicon carbide–silicon to create multilayer coatings for the other three SDO EUV wavelengths.

The Laboratory team, which includes Soufli, Eberhard Spiller, Jeff Robinson, Sherry Baker, and Jay Ayers, used a magnetron sputtering deposition system combined with a velocity modulation technique to achieve the precision SDO multilayer coatings. (See *S&TR*, October 2002, pp. 10–11.) By adjusting the bilayer thickness in the multilayer coating, researchers can "tune" each mirror to selectively reflect a specific EUV wavelength of solar radiation.

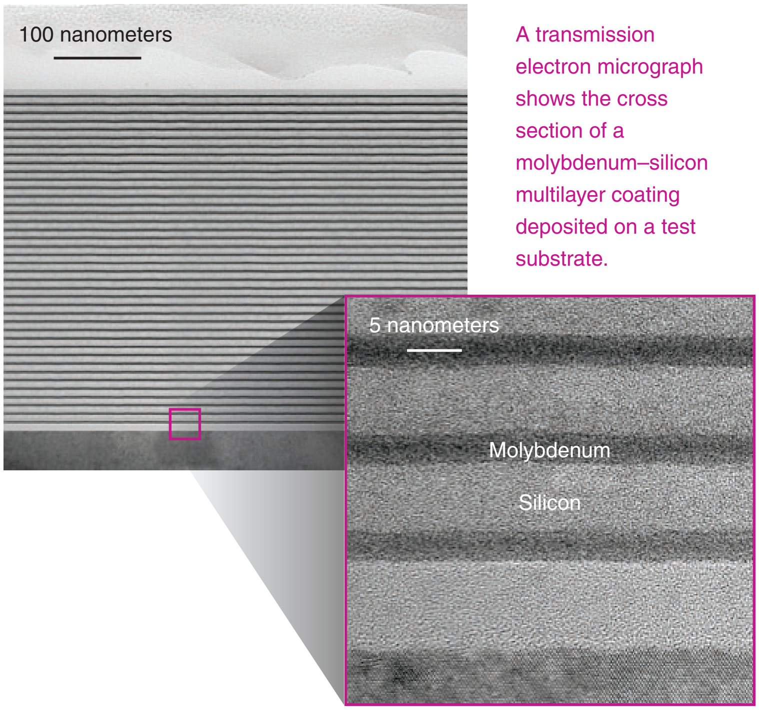


The four AIA telescopes each contain a large primary concave mirror (200 millimeters in diameter) and a smaller, secondary convex mirror (80 millimeters in diameter). Each mirror assembly can reflect light at two wavelengths.

Overcoming Obstacles

Each of the four AIA telescopes contains a primary and secondary curved mirror designed to reflect light at two wavelengths. Two different reflective multilayer coatings must be deposited on each D-shaped "half" of the circular mirror substrate's front surface to achieve this result. Each coating acts as a reflective filter that separates the desired EUV wavelength from other visible, ultraviolet, and EUV light emitted from the Sun. Light entering the telescope reflects off the larger, concave primary optic (200 millimeters in diameter) onto the convex secondary optic (80 millimeters in diameter), which then reflects the light back through a small hole in the center of the primary optic. A detector behind this mirror measures and records the light for imaging.

The Livermore team had to overcome several challenges to create the multilayer optics with the precision and quality needed for SDO. A major task was trying to create a uniform layer of material across the curved surface of the optic. "Each multilayer coating must reflect at the same wavelength (to within a couple percent) across the entire curved mirror segment," says Soufli. "The challenge was to control the deposition process in a way that achieves a layer of constant thickness across the concave or



A transmission electron micrograph shows the cross section of a molybdenum–silicon multilayer coating deposited on a test substrate.

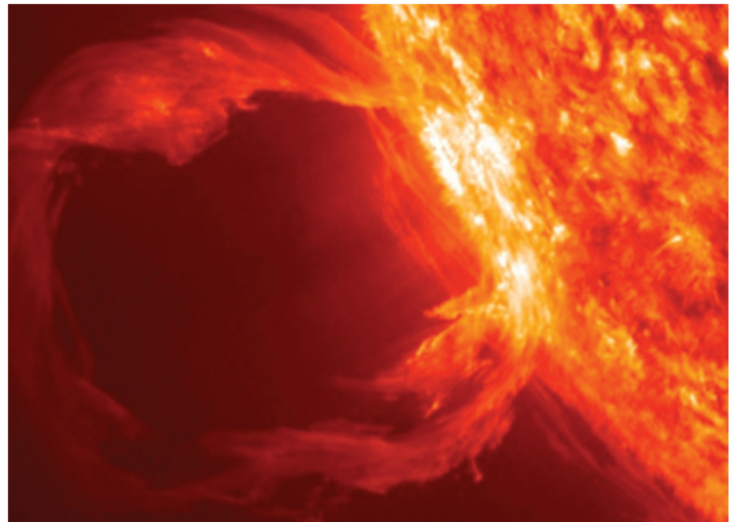
convex mirror surface. If the layer thickness differed from the desired specification by more than one-tenth of a nanometer, the SDO images would be degraded." During deposition, the velocity modulation technique allows for precise control of the multilayer thickness to compensate for the curvature of the optic. Using a custom-developed algorithm, researchers can adjust the speed of the deposition platter that holds the optic as it passes under the sputtering materials to achieve the desired thickness.

Additionally, because the multilayer coating could be deposited only over one-half of the optic at a time, the team needed a way to prevent material from being deposited on the other half of the optic and to minimize the area across the middle where the two coatings overlap. The solution was an optimized hardware mask that covers half of the circular optic as the other side is being coated. "We had to get the mask as close to the mirror surface as possible without actually touching it," says Soufli.

During deposition, particles from the sputtered material can bounce off the edge of the mask and land near and under it, an effect that is referred to as "shadowing." The area on the optic affected by shadowing, which includes the region where the two coatings overlap, does not reflect EUV light efficiently. "Think of the mask as an awning attached to a house during a rain storm," says Soufli. In this situation, most of the area underneath the awning will remain protected, but a few drops will land under the covering. "We engineered the mask to minimize detrimental shadowing effects on the area being coated, thus greatly improving the performance of the SDO multilayer optics."

The substrates onboard SDO were fabricated of ZERODUR® glass material and polished by commercial vendors. Each flight substrate, prior to multilayer deposition, was inspected by the Livermore researchers using atomic force microscopy. This technique enabled them to determine the substrate's surface roughness and other possible defects that could diminish reflective performance.

Before the finished optics were installed, the reflective performance was measured using the reflectometer facility on Beamline 6.3.2 at the Advanced Light Source, which is operated by the Center for X-Ray Optics at Lawrence Berkeley National Laboratory. "The peak EUV wavelength and reflectivity were measured at several locations across the surface of each mirror, thus creating 'maps' of the mirrors' experimental performance as they would operate onboard SDO," says Soufli. These calibration tests provided essential data that make it possible to accurately interpret the data transmitted by the AIA instrument.



SDO is enabling scientists to capture impressively high-resolution images of the Sun's physical processes. For example, this image shows a prominence eruption, which corresponds to an extreme ultraviolet emission line of ionized helium. (Courtesy of NASA.)

A Hot Topic

Over the course of SDO's five-year mission, scientists will use the collected images of the Sun to better understand space weather, for example, how the Sun's magnetic field contributes to activity such as solar flares and coronal mass ejections. By studying the Sun's physical processes in greater detail, scientists can improve predictions of solar activity, which can aid in protecting spacecraft crews as well as Earth's electrical and communications infrastructure. Equipped with Livermore's precision multilayer mirror technology, SDO is illuminating the Sun's inner workings and outward manifestations of those processes to provide essential data about Earth's most important star.

—Caryn Meissner

Key Words: Advanced Light Source, Atmospheric Imaging Assembly (AIA), extreme ultraviolet (EUV) light, magnetic field, magnetron sputtering deposition, multilayer mirror, solar corona, Solar Dynamics Observatory (SDO), solar physics, Sun.

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